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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 767

THE EFFECTS OF ENGINE SPEED AND MIXTURE TEMPERATURE

ON THE KNOCKING CHARACTERISTICS OF SEVERAL FUELS

By Dana W. Lee
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SUMMARY

Six 100-octane and two 87-octane aviation engine
fuels were tested in a modified C.F.R. variable-compres-
sion engine at 1,500, 2,000, and 2,500 rpm. The mixture
temperature was raised from 50° to 300° F in approximately
50° steps and, at each temperature, the compression ratio
was adjusted to give incipient knock as shown by a cathode-
ray indicator. The results are presented in tabular form.

The results are analyzed on the assumption that the
conditions which determine whether a given fuel will knock
are the maximum values of density and temperature reached
by the burning gases. A maximum permissible density fac-
tor, proportional to the maximum density of the burning
gases just prior to incipient knock, and the temperature
of the gases at that time were computed for each of the
test conditions. Values of the density factor were plot-
ted against the corresponding end-gas temperatures for the
three engine speeds and also against engine speed for sev-
eral end-gas temperatures.

The maximum permissible density factor varied only
slightly with engine speed but decreased rapidly with an
increase in the end-gas temperature. The effect of chang-
ing the mixture temperature was different for fuels of
different types. The results emphasize the desirability
of determining the antiknock values of fuels over a wide
range of engine and intake-air conditions rather than at
a single set of conditions.

INTRODUCTION

A method of expressing the relative maximum power-
output possibilities of aviation engine fuels for a wide
range of engine operating conditions has been developed

by Rothrock and Biermann. The method is described in reference 1 and is illustrated with data from several single-cylinder test engines using different types of fuel. Because the maximum performance that may be obtained with most aviation fuels depends on their knocking characteristics, the conditions affecting knock are used as the basis of comparison. The assumption is made that the conditions which determine whether a given fuel will knock are the maximum density and temperature reached by the burning gases. It would be extremely difficult to determine these conditions directly. Rothrock and Biermann therefore developed equations with which the gas density and temperature resulting in incipient knock could be estimated from certain engine and inlet-air conditions. The conditions most likely to affect the density and the temperature of the gases were concluded to be:

     (a) Compression ratio.

     (b) Inlet-air pressure.

     (c) Inlet-air temperature.

     (d) Spark advance.

     (e) Fuel-air ratio.

     (f) Combustion-chamber size and shape.

     (g) Wall temperature of combustion chamber and cylinder.

     (h) Engine speed.

The object of the tests described in this report was to determine the effects of engine speed and mixture temperature on the knocking characteristics of several aviation engine fuels of different types, using the method presented in reference 1, and thereby to check further the usefulness of the method.

Some of the listed engine and inlet-air conditions must be kept constant in any one test program if the number of tests is to be held to a reasonable limit. Conditions (f) and (g) were rendered constant for these tests by using only one test engine which, furthermore, had evaporative cooling. Condition (e) was kept constant by always using the fuel-air ratio that gave maximum engine power.

One set of tests was made with the spark advance set for
maximum power in each case and another set of tests was
made with a constant spark-advance setting. The inlet-
air pressure was atmospheric in every case and so was
practically constant. For each fuel, the remaining vari-
ables were therefore inlet-air temperature, engine speed,
and compression ratio.

With each fuel at each engine speed and at each mix-
ture temperature, the compression ratio was raised until
incipient knock began. The test results are presented in
tabular form. A maximum permissible density factor, pro-
portional to the density of the burning gases in the end
zone just prior to incipient knock, and the temperature
of the gases at that time were computed for each test con-
dition. The computed results are presented as curves.

The tests were conducted during 1938 at the Langley
Field laboratories of the National Advisory Committee for
Aeronautics.

APPARATUS

The engine used was a standard C.F.R. variable-com-
pression single-cylinder fuel-rating unit of 3-1/4-inch
bore and 4-1/2-inch stroke with the following modifica-
tions: Instead of being belt-connected to a constant-speed
electric motor, it was direct-connected to a cradle-type
electric dynamometer; a high-speed crankcase made possible
the conduction of tests at any speed up to 3,000 rpm; the
three-bowl adjustable-level carburetor was replaced by an
automobile-type downdraft carburetor in which the fuel sup-
ply to the main jet was manually controlled by a needle
valve and all the other jets were blocked off. Unshrouded
sodium-cooled valves were used for both intake and exhaust.

Electric heating units in a surge tank controlled the
temperature of the air supplied to the carburetor. The
readings of a mercury-in-glass thermometer installed in
the intake manifold between the carburetor and the engine
were used as indications of the temperature of the gasoline-
air mixture.

A photograph of the engine used is shown in figure 1.
The electric air heater is above the engine and the cathode-
ray oscillograph used as a knock indicator is in the lower
right-hand corner. The engine is shown equipped with a

manifold fuel-injection system. For the present tests, however, it was equipped with a carburetor.

The ignition system was modified to operate from the 230-volt direct-current line to which the dynamometer was connected. (See fig. 2.) Ordinary incandescent electric lamps were used to reduce the voltage for the primary circuit and, as the direct-current line was not grounded at the generator, both breaker points were insulated from the ground to guard against accidents due to stray grounds. This arrangement eliminated the necessity for a battery or a magneto. An aviation spark plug (BG-3B2) was used. The spark timing was manually controlled. The variation in spark timing was about ±0.5 crank degree at 2,500 rpm.

A piezoelectric crystal pick-up, installed in the opening ordinarily occupied by the bouncing pin, and a cathode-ray oscillograph enabled the operator to keep a close check on the rate of combustion. No bouncing pin was used in these tests. Incipient knock could be detected by the appearance of a high-frequency vibration in the pressure-time diagram on the oscillograph screen at engine conditions less severe than those required to produce audible knock. A more sensitive indication of this incipient knock was obtained by inserting the single-differentiating filter circuit shown in figure 3 between the oscillograph and its amplifier. The screen then showed the rate of change of pressure with frequencies of the order of the engine speed largely suppressed but with the knocking frequencies unaffected, and a higher amplification could therefore be used.

Distilled water was used in the evaporative-type cooling system, and a continuous indication of the fuel-air ratio was given by an Englehard fuel-air ratio meter.

FUELS

One of the fuels was the standard C.F.R. S-1 reference fuel, a technical grade of iso-octane with an octane rating of almost 100. Three other fuels were blends of S-1 and M-1 (a reference fuel having an octane number of about 18) with enough tetraethyl lead added to raise the octane number to 100, as determined by the Army method. The proportions of S-1, M-1, and tetraethyl lead in these fuels were established by the Matériel Division at Wright Field

and are given on the appropriate figures of this report.
Ethyl fluid was used in the fuels in the proportion of
1.53 ml of fluid for 1 ml of tetraethyl lead.

Two other fuels rated at 100 octane by the Army method
were tested. These fuels were obtained from Wright Field
and were designated PPF-566 and PPF-580. Fuel PPF-566 was
a toluene blend and fuel PPF-580 was an isopropyl ether
blend.

The final two fuels were obtained from an aircraft-
engine manufacturer and were designated N-87 and X-87.
Both fuels had been tested by the C.F.R. motor method
(A.S.T.M.) and had been given a rating of 87 octane num-
ber. The N-87 fuel was described as being a "conventional"
aviation gasoline; the X-87 fuel was termed "unconvention-
al" and the manufacturer stated that it seemed to be su-
perior in octane number to N-87 when used in an aviation
engine at high specific output.

PRELIMINARY TESTS

Preliminary tests made with each fuel at various com-
pression ratios, fuel-air ratios, and spark-advance angles
showed that the greatest engine power was always obtained
at an indicated fuel-air ratio of about 0.077; this value
was therefore selected as standard for all performance
tests.

The spark-advance angle for maximum power with atmos-
pheric intake-air density, hereinafter called the optimum
spark-advance angle, always decreased as the compression
ratio was increased. Optimum spark-advance angles were
determined for the S-1 fuel with 1.5 ml of tetraethyl
lead per gallon added to prevent knocking, and these val-
ues were used for the performance tests at optimum spark-
advance angles with the blends of S-1 and M-1 fuels and
also for the tests with the two fuels of 87 octane number.
Separate determinations of the optimum spark-advance angle
for the PPF-566 and PPF-580 fuels were made because these
two fuels contained compounds whose chemical natures were
radically different from those of the S-1 and the M-1
fuels. Because the supply of PPF-580 and PPF-566 fuels
was limited, the optimum spark-advance angle was determined
at only two or three compression ratios and a straight-line
relation was assumed to exist between the optimum angle

and the compression ratio. During the performance tests, a much higher compression ratio for incipient knock was obtained than had been anticipated; extrapolation of the optimum spark-advance-angle curves was therefore necessary. Again a straight-line relation was assumed.

The values of the optimum spark-advance angle were determined at a mixture temperature of 200° F. Tests indicated that the variation in optimum angle with mixture temperature was too small to be considered in this investigation.

PERFORMANCE TESTS

Each of the eight fuels was tested at engine speeds of 1,500, 2,000, and 2,500 rpm and at mixture temperatures from about 50° or 100° F to about 300° F in approximately 50° steps. All tests were made at full throttle and with atmospheric intake pressure. At each test condition, the spark-advance angle was continuously adjusted for maximum power as the compression ratio was varied until incipient knock was indicated on the oscillograph screen. The ignition switch was then momentarily opened to check for autoignition. In no case did autoignition occur. In addition to the tests with optimum spark-advance angles, the six 100-octane fuels were tested with a fixed spark-advance angle of 30°.

No control nor measurement of atmospheric humidity was attempted. Although it was recognized that humidity variations have small effects on knock, the magnitude of those effects was considered to be negligible in comparison with the larger effects being studied. (See reference 1.)

The test results are presented in table I. In order to make the table more concise, the mixture-temperature readings for the three engine speeds and the two spark settings have been averaged. The maximum deviation of any reading from the average was 9°.

With most of the fuels, the maximum permissible compression ratio increased with increasing engine speed except at the highest mixture temperature (300° F), at which there was a slight decrease. The fuel containing 79 percent S-1, however, when tested at a constant spark-advance angle of 30°, and the N-87 fuel at the optimum spark-advance angle had increasing maximum permissible compression ratios with increasing engine speed at all mixture tem-

peratures. The PPF-566 fuel, on the other hand, had a decrease at all temperatures.

In nearly every case the maximum permissible compression ratio decreased markedly as the mixture temperature was increased. The decrease in compression ratio was greater with the optimum than with the constant spark-advance angle. In most cases, the maximum permissible compression ratio was greater for the 30° spark advance than for the optimum spark-advance angle.

Values of the maximum permissible compression ratio greater than 8 for the PPF-580 fuel and 10 for the PPF-566 fuel with optimum spark-advance angle are questionable because of the necessity of extrapolating the curves in figure 4. Comparison with the other data in table I indicates that these questionable compression ratios are probably too high.

ANALYSIS

The results of the performance tests were analyzed by the method presented in reference 1, in which the following equations are given for a density factor that is proportional to the maximum gas density at the end of normal combustion and for the maximum gas temperature at that time:

$$K\rho_3 = \frac{RP_1}{T_1}\left(1 + \frac{H}{c_v T_1 R^{\gamma-1}}\right)^{\frac{1}{\gamma}} \tag{1a}$$

$$T_3 = T_1 R^{\gamma-1}\left(1 + \frac{H}{c_v T_1 R^{\gamma-1}}\right)^{\frac{\gamma-1}{\gamma}} \tag{2a}$$

in which

ρ_3　maximum gas density at end of normal combustion.

T_3　maximum absolute gas temperature at end of normal combustion.

R　compression ratio.

P_1 absolute inlet-air pressure.

T_1 absolute inlet-air temperature.

H   heat content per pound of mixture.

c_v specific heat of mixture at constant volume.

γ adiabatic coefficient.

K   constant.

In equation (1a), RP_1/T_1 represents the gas density at the end of the compression stroke and the expression

$$\left(1 + \frac{H}{c_v T_1 R^{\gamma-1}}\right)^{\frac{1}{\gamma}}$$ represents the further compression

of the gas in the end zone during the combustion period. Similarly, in equation (2a), $T_1 R^{\gamma-1}$ represents the com-

pression temperature and the expression $\left(1 + \frac{H}{c_v T_1 R^{\gamma-1}}\right)^{\frac{\gamma-1}{\gamma}}$

represents the temperature increase in the end gas caused by the compression in this zone during the combustion. Subscripts 1 and 3 refer to definite stages in the preparation and the burning of the fuel charge, 1 being the beginning of the compression stroke and 3 being the completion of combustion.

If now the values of R, P_1, and T_1 used in the equations are those causing incipient knock, the values of $K\rho_3$ and T_3 will refer to the density and the temperature of the gases in the knocking zone just before incipient knock occurs. The following analysis consists in the computation and the study of these two factors.

No account was taken in reference 1 of changes in the temperature and the pressure of the air during its passage through the carburetor and the intake passages and in the cylinder during the intake stroke. Many changes may take place. The pressure may be increased by ramming action or decreased by throttling at the valves. The temperature may be increased by turbulence and will be decreased by

vaporization of the fuel. Heat exchanges between the
mixture and the combustion-chamber walls during the in-
take stroke are also important. In this analysis, some
of these changes will be considered.

Neither the pressure nor the temperature of the air
at the beginning of the compression stroke can be conven-
iently determined in routine engine tests, but the weight
of air consumed per cycle can be measured by a suitable
flowmeter, such as a calibrated thin-plate orifice. Un-
fortunately, such data were not obtained at the time each
test was made. As the best substitute available for such
data, the results of some air-consumption tests made at
the conclusion of the test program will be used.

The engine was operated at the same fuel-air ratio,
speeds, and mixture temperatures as for the maximum-com-
pression-ratio tests and the air consumption per cycle
was measured with a gasometer and an electrically operated
engine revolution counter. The results are presented in
figure 5 in the form of density correction factors F,
which are simply the ratios of the volume of the air at
atmospheric density actually consumed per cycle to the en-
gine displacement. The presence of the large air heater
and the long intake pipe apparently resulted in a ramming
action at an engine speed of 2,000 rpm. The curves have
been extrapolated from a mixture temperature of 100° F to
50° F. Compression ratio 6 was the only compression ratio
used. Other tests made on this engine at a mixture tem-
perature of 50° F have indicated that increasing the com-
pression ratio from 6 to 11 results in a decrease in the
density correction factor of about 0.030 at 1,500 rpm,
0.015 at 2,000 rpm, and practically 0 at 2,500 rpm. No
corrections for the effects of compression ratio on the
density correction factor, however, were attempted.

The gas density at the beginning of the compression
stroke can now be estimated by multiplying the density of
the air entering the heater by the proper density correc-
tion factor F; equation (1a) then becomes

$$K\rho_3 = \frac{RP_0}{T_0} \; F \left(1 + \frac{H}{c_V T_1 R^{\gamma-1}} \right)^{\frac{1}{\gamma}} \tag{1b}$$

in which the subscript o refers to the state of the air
at atmospheric conditions.

No further changes in the equations have been made
but mixture temperatures rather than air temperatures were
used for T_1.

The density correction factors eliminate the effects
of changes in the engine speed and the mixture temperature
on the mixture density at the beginning of the compression
stroke and thus reveal the true effects of engine speed
and mixture temperature on the knocking tendencies of the
fuels.

Some of the data presented in reference 1 were plot-
ted as RP_1/T_1 against T_1. Justification for the use
of these simplified forms of equations (1a) and (2a) was
found in the fact that the results of tests made over a
wide range of inlet-air pressures, temperatures, and com-
pression ratios could be represented as a single curve
for any one fuel. The fact that the present tests were
conducted at constant inlet-air pressure made it impossible
to determine whether the simplified coordinates could be
used in this report. Some data from supercharging tests
on a C.F.R. engine by Boerlage and given in table VI of
reference 1 indicate that the simpler forms should not be
used for test results from a C.F.R. engine.

Values of $K\rho_3$ and T_3 were therefore computed from
equations (1b) and (2a) for each of the test conditions
by substituting in the equations the values of R, P_0,
T_0, and T_1 from the test data, the values of the den-
sity correction factor from figure 5, and the following
assumed values for the other factors: 1,160 Btu per pound
of mixture for H; 0.25 Btu per pound per degree Fahren-
heit for c_v; and 1.29 for γ. Pressure was expressed
in inches of mercury and temperature in degrees Fahrenheit,
both absolute.

The values of the maximum permissible density factor
$K\rho_3$ were plotted against the end-gas temperature T_3.
The results of the tests with the six 100-octane fuels
are shown in figure 6 for the optimum spark-advance angle
and, in figure 7, for the spark-advance angle of 30°.
(The supply of the toluene blend was exhausted before tests
could be completed at 1,500 and 2,500 rpm with optimum
spark-advance angle.) Although all six fuels have the
same octane rating as determined by the Army method,
marked differences in the fuels are shown from the severity
of the operating conditions at which incipient knock oc-
curred. The toluene blend, which withstood the most se-

vere conditions, was best; the isopropyl ether blend was
next; and the four fuels containing S-1, M-1, and tetra-
ethyl lead were lowest and fairly well grouped.

The maximum permissible density factor decreased rap-
idly with increasing end-gas temperature for all the fuels.
The rate of change was greatest with the toluene blend,
followed by the isopropyl ether blend and the S-1 refer-
ence fuel. The slope of the curves for the three blends
of S-1, M-1, and tetraethyl lead were about the same and
slightly less than for the S-1 fuel alone.

The effect of engine speed on the maximum permissible
density factor is more clearly shown in figures 8 and 9,
which are cross plots of the curves in figures 6 and 7 at
three values of the end-gas temperature. The cross plots
show a slight increase in the maximum permissible density
factor with increasing engine speed for most of the fuels
at the lowest value of the end-gas temperature. As the
end-gas temperature increases, the slopes of the curves
decrease and even become negative in some cases.

Changes in the end-gas temperature are primarily a
result of changes in the mixture temperature; the three
groups of curves in figure 8 and 9 may therefore be con-
sidered to represent low, medium, and high mixture temper-
atures. The fact that the slopes of the curves change
with changes in the end-gas (or mixture) temperature sug-
gests that the effect of engine speed on the maximum per-
missible density factor may be a result of changes in the
amount and the direction of heat transfer between the en-
gine and the mixture during the intake and compression
strokes rather than a result of any effect of time on the
knock itself. At low mixture temperatures, for example,
the mixture will absorb heat from the engine and the
amount absorbed will decrease as the engine speed increases.
The compression ratio required to produce incipient knock
will therefore increase and the computed value of the maxi-
mum permissible density factor will be greater.

The computed values of K_{ρ_3} plotted against T_3 for
the two 87-octane fuels are shown in figure 10. Tests·
were made only at the optimum spark-advance angle for these
fuels. It is especially significant that the maximum per-
missible density factors for the two fuels are nearly
equal at the highest values of the end-gas temperature be-
cause the data for these points were obtained at a mixture
temperature of about 300° F, the temperature used in the

rating method which established them as 87-octane fuels. Figure 10 shows that these two fuels have equal antiknock properties only at a mixture temperature of about 300° F. At lower mixture temperatures, the X-87 fuel will have a higher antiknock rating at all speeds and, at higher mixture temperatures, the N-87 fuel will probably have the higher antiknock rating.

CONCLUSIONS

1. There were indications that the commonly observed effects of engine speed on the knocking characteristics of fuels are due more to changes in the temperature and the density of the mixture during the intake stroke than to any effect of time on knock itself.

2. For all the fuels tested, increasing the mixture temperature resulted in a marked decrease in the compression ratio required to produce incipient knock. The rate of change, however, was much greater with some of the fuels than it was with others.

3. The test results emphasize the desirability of determining the antiknock values of fuels over a wide range of engine and intake-air conditions rather than at a single set of conditions.

Langley Memorial Aeronautical Laboratory,
     National Advisory Committee for Aeronautics,
          Langley Field, Va., April 2, 1940.

REFERENCE

1. Rothrock, A. M., and Biermann, Arnold E.: The Knocking
     Characteristics of Fuels in Relation to Maximum Per-
     missible Performance of Aircraft Engines. T.R. No.
     655, N.A.C.A., 1939.

TABLE I

EFFECTS OF ENGINE SPEED AND MIXTURE TEMPERATURE ON THE MAXIMUM PERMISSIBLE COMPRESSION RATIO

Fuel	Average mixture temperature (°F)	Compression ratio for incipient knock					
		With optimum spark advance			With constant spark advance (30°)		
		1500 rpm	2000 rpm	2500 rpm	1500 rpm	2000 rpm	2500 rpm
100-percent S-1	48	---	---	---	8.90	9.30	10.10
	103	8.30	8.65	9.20	9.15	9.45	9.90
	152	8.02	8.20	8.35	9.15	9.50	9.80
	200	7.70	7.67	7.52	8.70	9.10	9.30
	250	7.35	7.12	6.82	8.70	8.70	8.70
	303	6.87	6.62	6.22	8.10	8.00	8.00
90-percent S-1 +10-percent M-1 +1.0 ml tetraethyl lead per gallon	50	---	---	---	7.90	8.20	8.90
	104	7.71	8.12	8.75	8.05	8.30	8.60
	151	7.54	8.28	8.75	8.00	8.45	8.80
	199	7.42	8.01	8.08	7.90	8.20	8.45
	253	7.24	7.61	7.57	7.45	7.65	7.65
	300	7.04	7.27	6.62	7.45	7.65	7.30
85-percent S-1 +15-percent M-1 +2.0 ml tetraethyl lead per gallon	53	---	---	---	8.50	8.90	9.80
	103	7.82	8.14	8.60	8.50	8.91	9.50
	152	7.81	8.16	8.53	8.50	8.80	9.30
	205	7.63	7.87	8.07	8.45	8.80	8.90
	252	7.45	7.82	7.60	8.10	8.70	8.50
	297	7.14	6.97	6.64	8.05	8.60	8.05
79-percent S-1 +21-percent M-1 +4.0 ml tetraethyl lead per gallon	64	---	---	---	8.75	8.75	9.95
	103	8.41	8.50	9.33	8.70	8.90	9.55
	151	8.22	8.54	9.06	8.40	9.10	9.80
	199	7.68	8.38	8.18	8.25	8.70	9.30
	250	7.83	8.16	7.80	8.05	8.70	8.80
	302	7.28	7.13	6.99	8.00	8.60	8.25
PPF-580 (isopropyl ether blend)	43	10.40	10.00	11.25	10.10	10.40	11.00
	108	10.80	9.80	10.40	10.30	10.10	10.40
	153	10.20	9.30	9.80	10.00	9.90	9.80
	198	9.50	8.50	9.00	9.30	9.35	9.20
	257	8.60	8.10	7.55	8.60	8.90	8.55
	305	8.10	7.00	7.00	8.30	8.00	8.00
PPF-566 (toluene blend)	52	---	12.15	---	13.00	12.15	11.65
	101	---	11.05	---	11.80	11.30	11.25
	151	---	10.80	---	11.35	10.95	10.40
	200	---	9.65	---	9.90	10.00	10.00
	245	---	8.70	---	9.70	9.20	8.90
	300	---	7.50	---	8.50	7.90	8.00
N-87	101	6.25	6.50	7.02	---	---	---
	150	6.50	6.40	6.72	---	---	---
	198	5.85	6.10	6.35	---	---	---
	250	5.85	5.70	5.90	---	---	---
	302	5.40	5.65	5.75	---	---	---
X-87	101	7.55	7.87	8.65	---	---	---
	149	7.05	7.35	7.95	---	---	---
	200	7.00	6.85	6.85	---	---	---
	250	5.97	6.20	6.18	---	---	---
	299	5.80	5.90	5.70	---	---	---
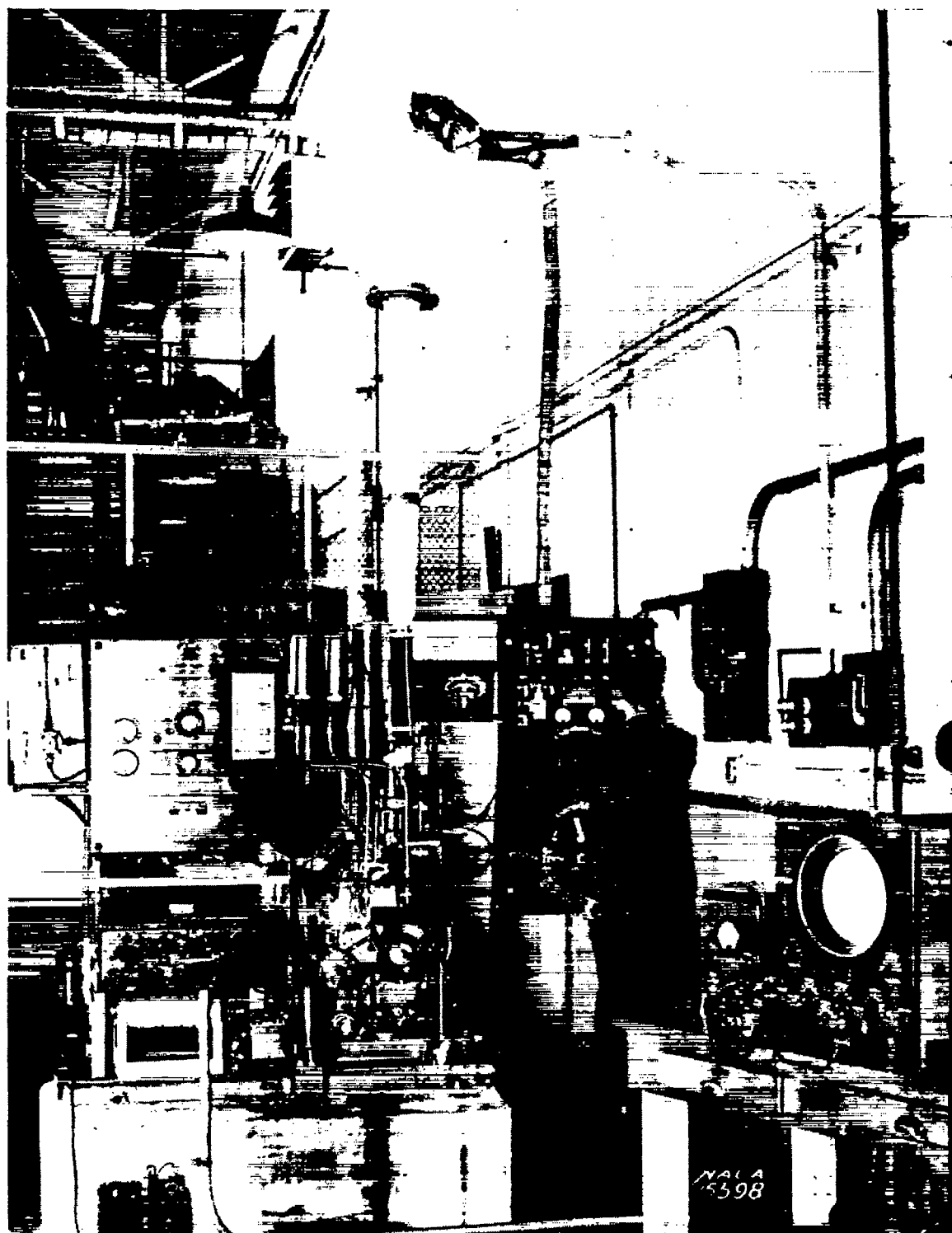
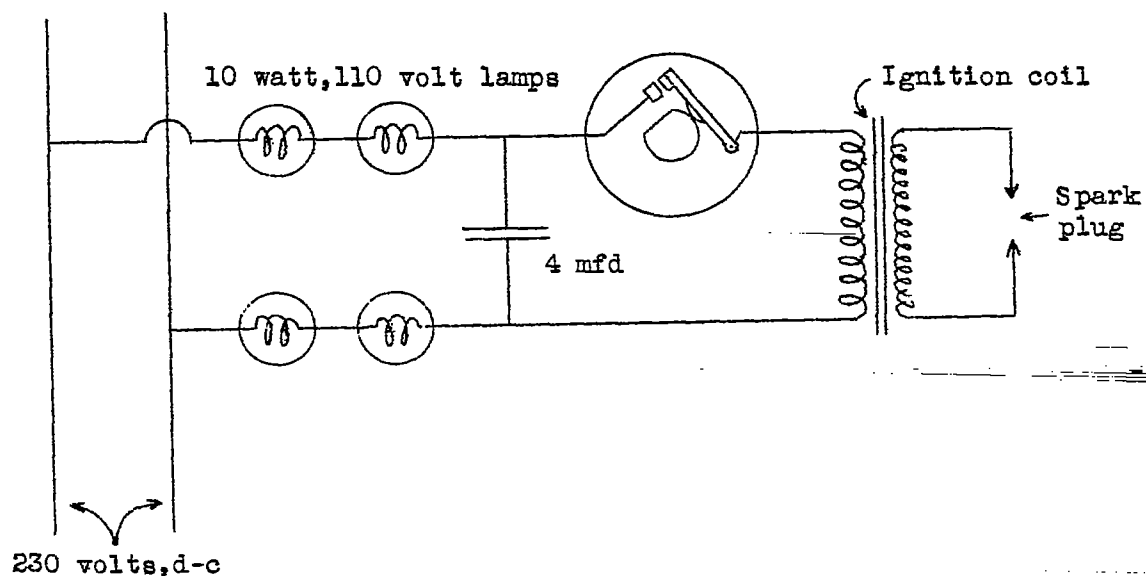Figure 1.- General view of test equipment.

10 watt, 110 volt lamps   Ignition coil

4 mfd   Spark
                                            plug

230 volts, d-c

Figure 2.- Diagram of spark-ignition circuit.

AMPLIFIER   OSCILLOGRAPH

.0002 mfd.

Input   Output   Vertical
                                           input

100,000 Ω

Shielded cable to
piezoelectric crystal pickup.
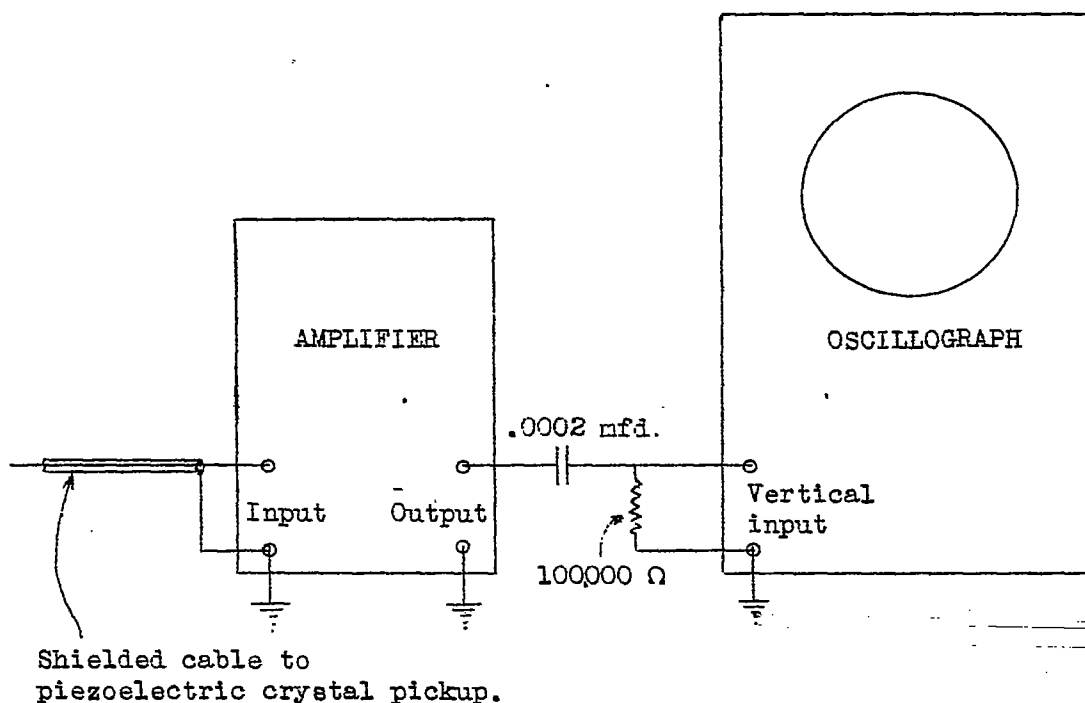
Figure 3.- Installation of cathode-ray oscillograph for indication
                of incipient knock.
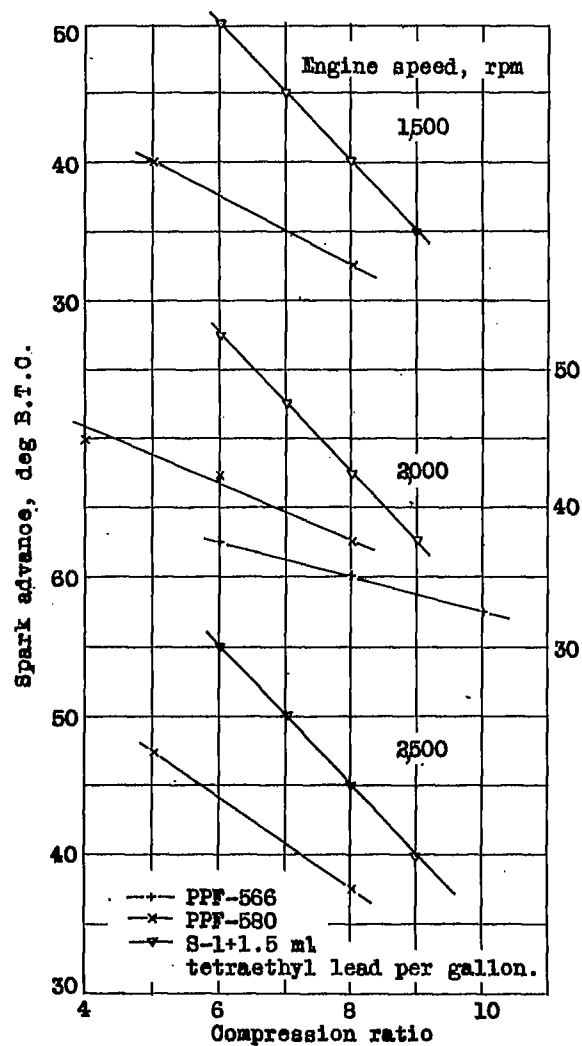
Figure 4.- Effects of engine speed and compression ratio on the spark advance for maximum power at atmospheric inlet pressure.
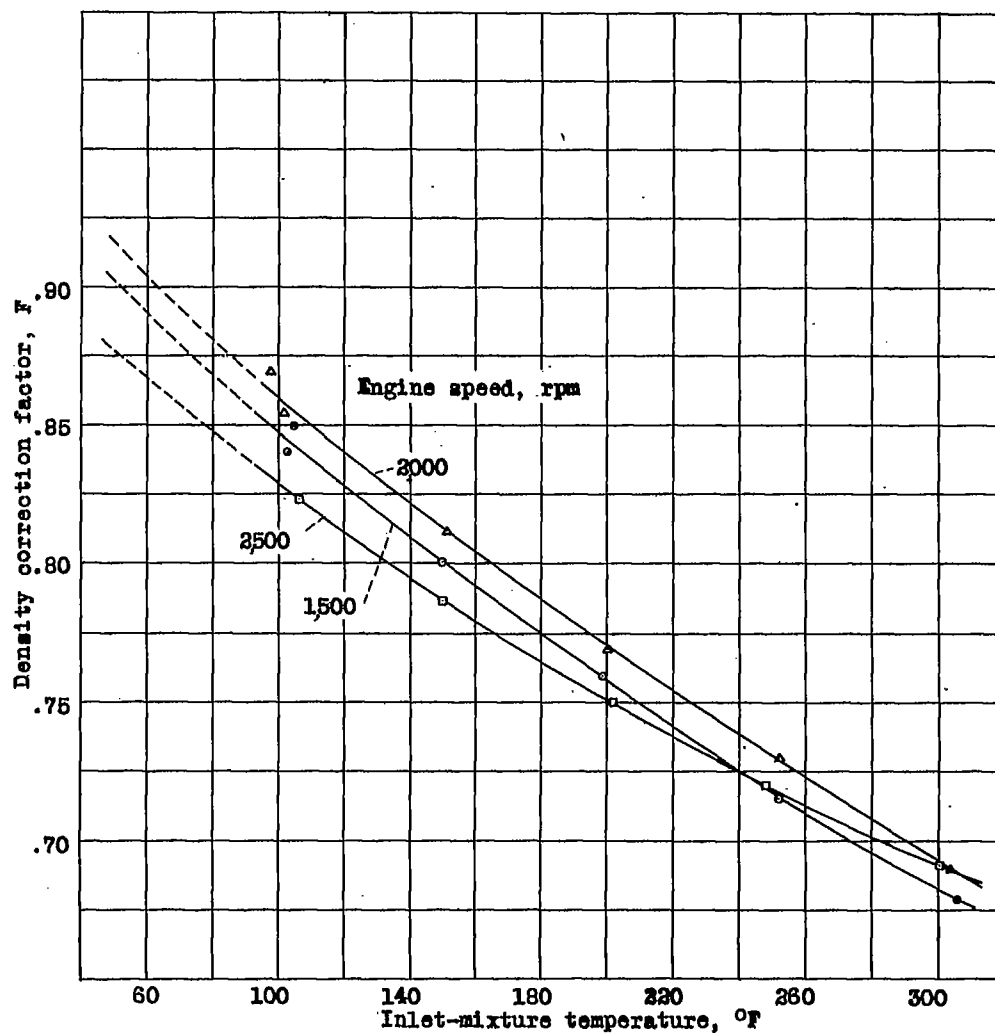
Figure 5.- Effect of engine speed and mixture temperature on the density correction factor.
Fuel-air ratio, 0.077; compression ratio, 6.

Key for Figs. 6,7.

- □ S-1 reference fuel.
- △ 90% S-1+10% M-1+1.0 ml tetraethyl lead per gallon.
- ○ 85% S-1+15% M 1+2.0 ml   "   "   "   "
- ◇ 79% S-1+21% M-1+4.0 ml   "   "   "   "
- ⋇ PPF-580 (U.S.Army isopropyl ether blend.)
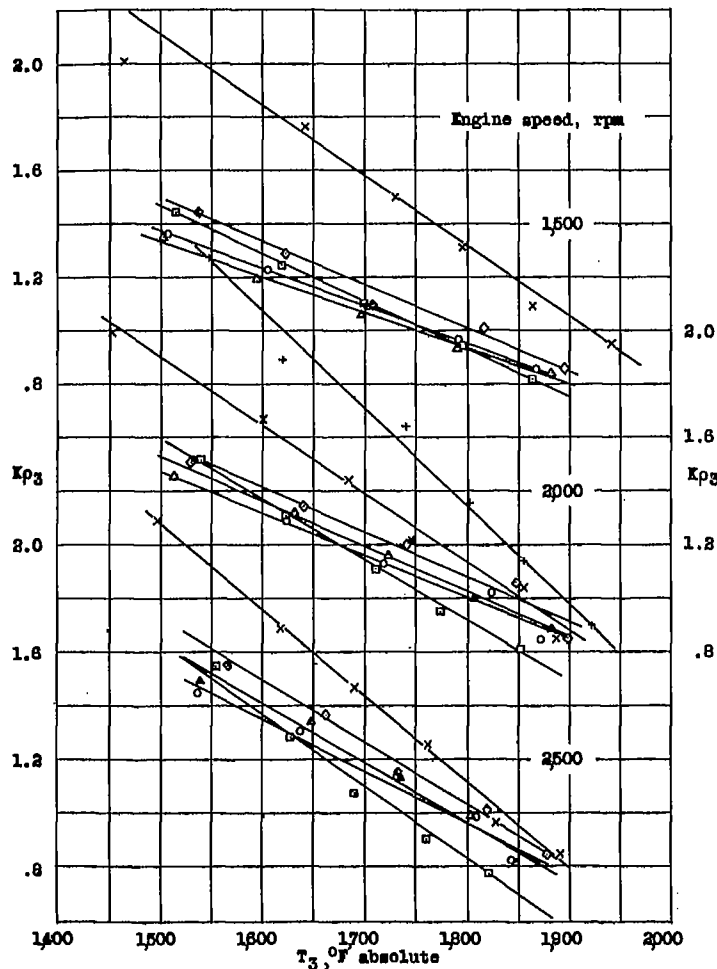- + PPF-588 (U.S.Army toluene blend.)

Figure 6.— Effect of computed end-gas temperature on the maximum permissible density factor. Optimum spark-advance angle.
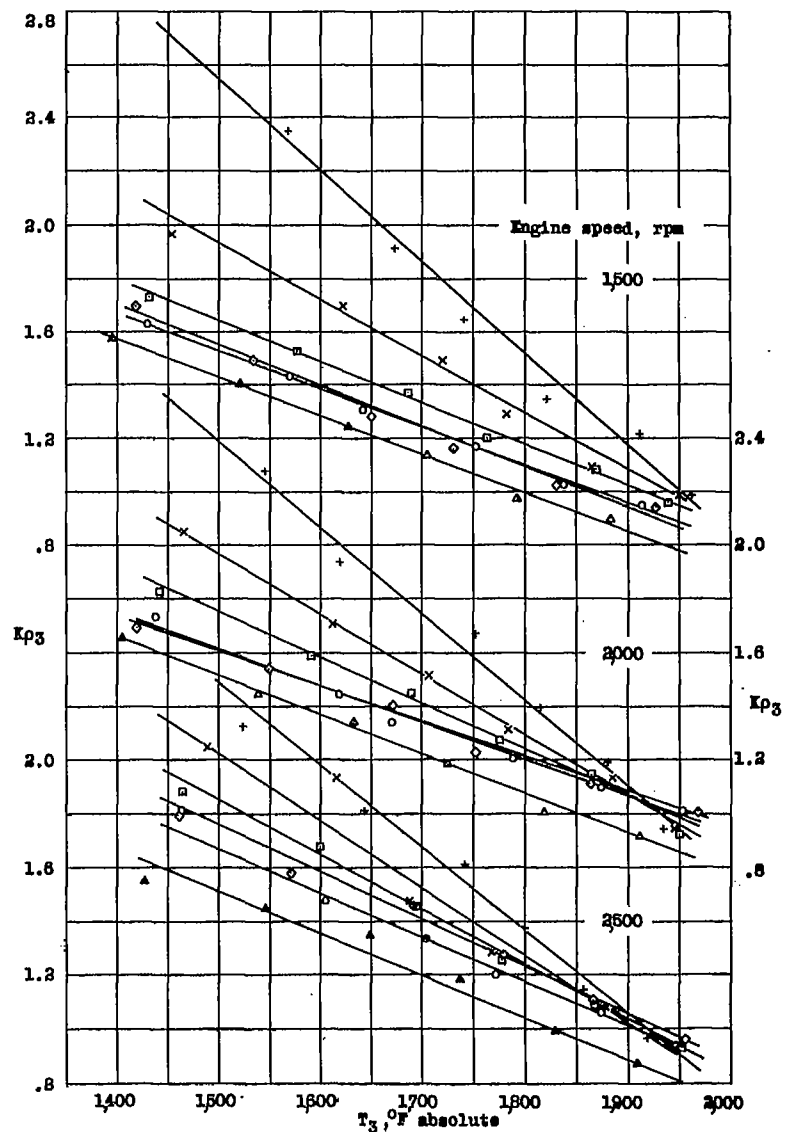

Figure 7.— Effect of computed end-gas temperature on the maximum permissible density factor. Spark-advance angle, 30°.
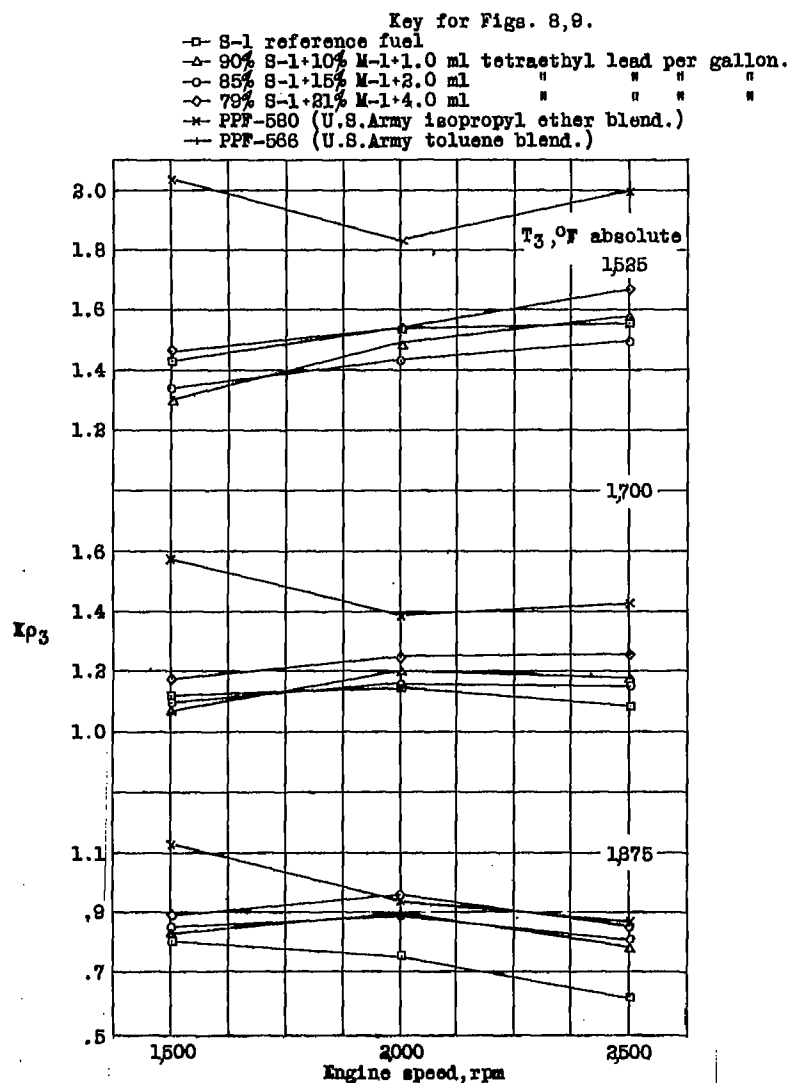
Key for Figs. 8,9.
- 8-1 reference fuel
- 90% 8-1+10% M-1+1.0 ml tetraethyl lead per gallon.
- 85% 8-1+15% M-1+2.0 ml   "   "   "   "
- 79% 8-1+21% M-1+4.0 ml   "   "   "   "
- PPF-580 (U.S.Army isopropyl ether blend.)
- PPF-566 (U.S.Army toluene blend.)

K_{ρ_3}

T_3,°F absolute

Engine speed,rpm

Figure 8.- Effect of engine speed on the maximum permissible
density factor. Optimum spark-advance angle.

K_{ρ_3}

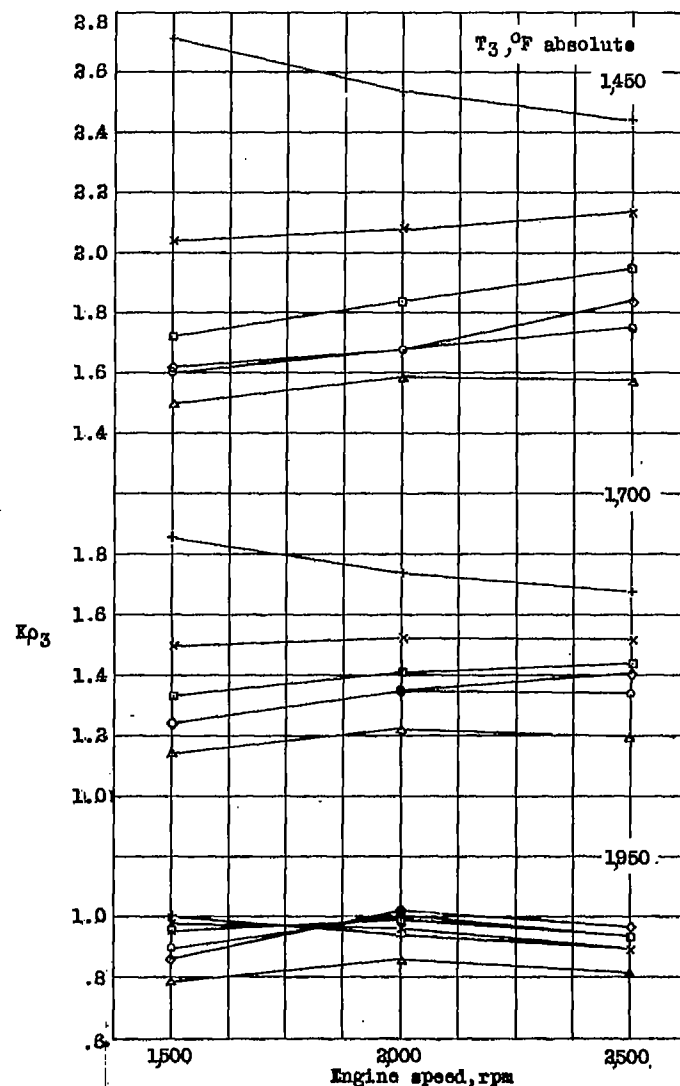T_3,°F absolute

Engine speed,rpm

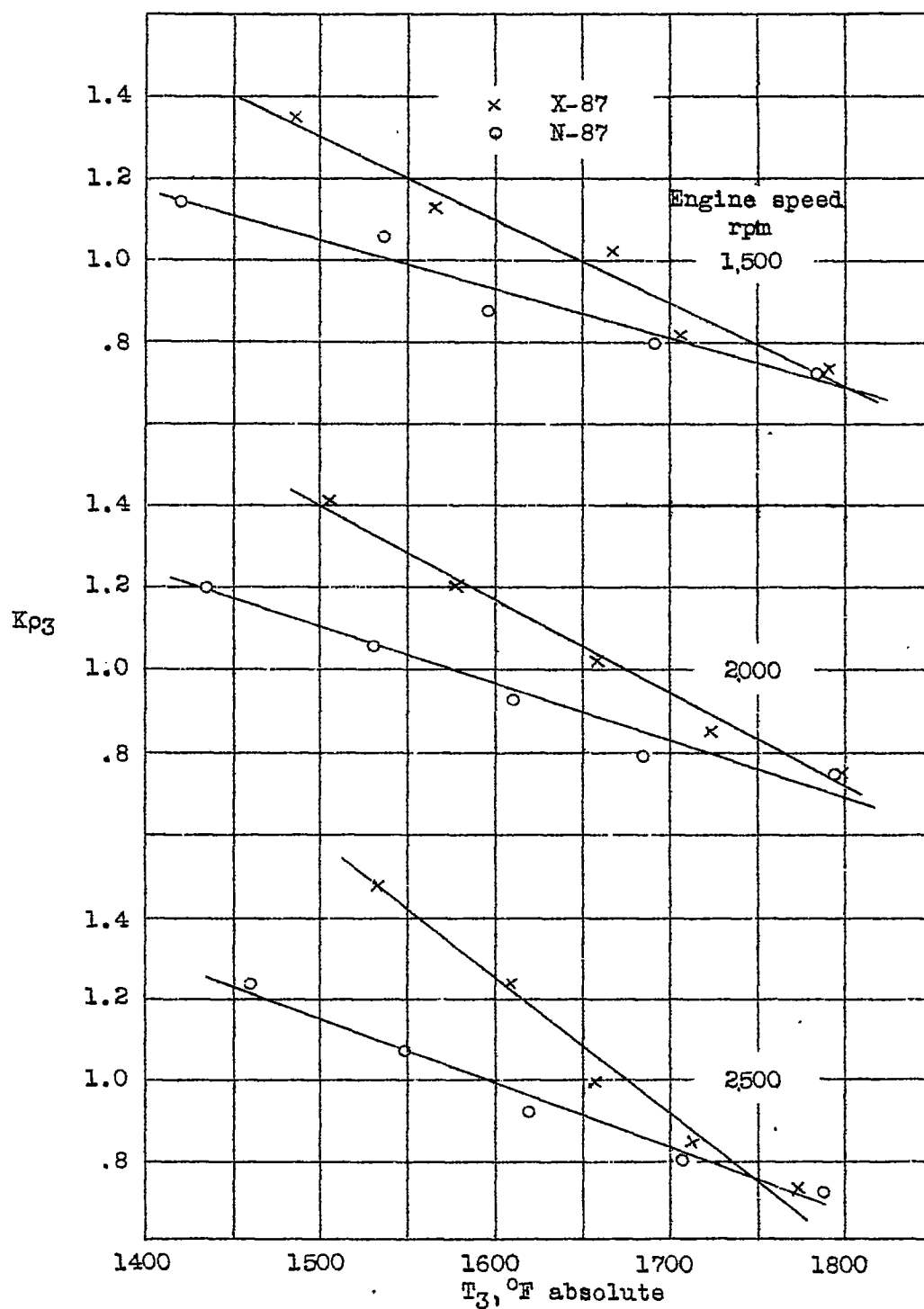Figure 9.- Effect of engine speed on the maximum permissible
density factor. Spark-advance angle, 30°.

Figure 10.- Effect of computed end-gas temperature on the maximum
permissible density factor. Optimum spark-advance angle.